(10)

AD_____

AD-A185 009

REPORT NO T28-87

ERGOGENIC INFLUENCE OF ERYTHROCYTE REINFUSION: AEROBIC POWER AND THERMOREGULATION

U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

JULY 1987

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

DISPOSITION INSTRUCTIONS

Destroy this report when no longer needed.

Do not return to the originator.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

ADA185009

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Res Inst of Env Med 6b. OFFICE SYMBOL (If applicable) SGRD-UE-MEP	7a. NAME OF MONITORING ORGANIZATION Same as 6.a.
6c. ADDRESS (City, State, and ZIP Code) Kansas Street Natick, MA 01760-5007	7b. ADDRESS (City, State, and ZIP Code) Same as 6.c.
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Same as 6.a. 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Same as 6.c.	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 3E162777 A879 PROJECT NO.: 879/BD TASK NO.: 121 WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) Ergogenic Influence of Erythrocyte Reinfusion: Aerobic Power and Thermoregulation

12. PERSONAL AUTHOR(S) W.A. Latzka, M.N. Sawka, S.R. Muza, R.R. Gonzalez, A.J. Young, K.B. Pandolf, R.C. Dennis, J.W. Martin, C.B. Wenger and C.R. Valeri

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Report	FROM _____ TO _____	July 1987	47

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	erythrocyte reinfusion, blood doping, thermoregulation, maximal oxygen uptake, Special Forces, blood volume, plasma volume, polycythemia

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

We measured the physical exercise capabilities of the U.S. Army Special Forces soldiers (male) and determined the subsequent ergogenic influence of autologous erythrocyte reinfusion. Twelve subjects (Ss) completed maximal exercise treadmill testing in a comfortable ~~(T_a = 20°C, T_{dp} = 9°C)~~ environment. Six Ss were later transfused with a 600 ml autologous erythrocyte ~~(50% Hct)~~ in a NaCl glucose-phosphate solution and completed identical maximal exercise tests approximately 3 and 10 days post-transfusion. For the 6 reinfused Ss, hemoglobin (Hb) and erythrocyte volume (RCV) increased 10% ($p<0.05$) and 11% ($p<0.05$), respectively, post transfusion. Reinfusion increased ($p<0.05$) $\dot{V}O_2$ max from 4.28 ± 0.22 $l \cdot min^{-1}$ (54±5 $ml \cdot kg^{-1} \cdot min^{-1}$) to 4.75 ± 0.42 $l \cdot min^{-1}$ (60 ± $ml \cdot kg^{-1} \cdot min^{-1}$) and 4.63 ± 0.21 $l \cdot min^{-1}$ (59 ± 6 $ml \cdot kg^{-1} \cdot min^{-1}$) at 3 and 10 days post-transfusion, respectively. No significant relationship was found between the individual change in RCV and Hb with $\dot{V}O_2$ max values to post-transfusion. Heat stress tests (HSTs) were administered approximately 2 wk pre- and 48 h post-infusion. After 30 min of rest in a 20°C antechamber, the HSTs consisted of a

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	Unclas
22a. NAME OF RESPONSIBLE INDIVIDUAL SGT William A. Latzka	22b. TELEPHONE (Include Area Code) 617-651-4853 22c. OFFICE SYMBOL SGRD-UE-MEP

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED

A1

19. Abstract (cont'd)

120 min exposure (two repeats of 15 min rest and 45 min treadmill walking) in a hot (35°C, 45% rh) environment while euhydrated. The following observations were made: 1) the increased erythrocyte volume was associated with a reduction in plasma volume (PV) and maintained the same blood volume as during the pre-infusion measurements; 2) polycythemia reduced total circulating protein but did not alter F-cell ratio, plasma osmolality, plasma protein content, or plasma lactate at or during exercise-heat stress; 3) polycythemia did not change the volume of fluid entering the intravascular space from rest to exercise-heat stress; 4) polycythemia tended to reduce the rate of heat storage during exercise-heat stress; 5) polycythemia caused an improved local sweating response. We conclude that induced polycythemia can have an ergogenic effect by increasing maximal aerobic power and enhancing the thermoregulatory response during exercise-heat stress.

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Approved for public release; distribution is unlimited.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

ACKNOWLEDGEMENTS

The authors express their appreciation to the volunteer members of the 10th Special Forces group and their leaders whose participation made this study possible. The authors gratefully acknowledge Tammy Doherty for statistical assistance and Patricia DeMusis for preparation of the manuscript.

TECHNICAL REPORT

NO. T28-87

ERGOGENIC INFLUENCE OF ERYTHROCYTE REINFUSION: AEROBIC POWER AND THERMOREGULATION

William A. Latzka, Michael N. Sawka, Stephen R. Muza, Richard R. Gonzalez, Andrew J. Young, Kent B. Pandolf, Richard C. Dennis*, James W. Martin, C. Bruce Wenger and C. Robert Valeri*

July 1987

U.S. Army Research Institute of Environmental Medicine

Natick, Massachusetts 01760-5007

and

*Naval Blood Research Laboratory

Boston, Massachusetts 02118

PREFACE

The methodology and findings of this report are or will be published in the open literature as follows:

Muza, S.R., M.N. Sawka, A.J. Young, R.C. Dennis, R.R. Gonzalez, J.W. Martin, K.B. Pandolf and C.R. Valeri. Elite special forces: Physiological description and ergogenic influence of blood reinfusion. Aviation, Space and Environmental Medicine 58:(In Press), 1987.

Sawka, M.N., R.C. Dennis, R.R. Gonzalez, A.J. Young, S.R. Muza, J.W. Martin, C.B. Wenger, R.P. Francesconi, K.B. Pandolf and C.R. Valeri. Influence of polycythemia on blood volume and thermoregulation during exercise-heat stress. Journal of Applied Physiology 62 (3):912-918, 1987.

Sawka, M.N., A.J. Young, S.R. Muza, R.R. Gonzalez and K.B. Pandolf. Erythrocyte reinfusion and maximal aerobic power: an examination of modifying factors. Journal of the American Medical Association 257 (11):1496-1499, 1987.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

We measured the physical exercise capabilities of the U.S. Army Special Forces soldiers (male) and determined the subsequent ergogenic influence of autologous erythrocyte reinfusion. Twelve subjects (Ss) completed maximal exercise treadmill testing in a comfortable (T_a = 20°C, T_{dp} = 9°C) environment. Six Ss were later transfused with a 600 ml autologous erythrocyte (50% Hct) in a NaCl glucose-phosphate solution and completed identical maximal exercise tests approximately 3 and 10 days post-transfusion. For the 6 reinfused Ss, hemoglobin (Hb) and erythrocyte volume (RCV) increased 10% ($p<0.05$) and 11% ($p<0.05$) respectively, post-transfusion. Reinfusion increased ($p<0.05$) $\dot{V}O_2$max from 4.28±0.22 l•min^{-1} (54±5 ml•kg^{-1}•min^{-1}) to 4.75±0.42 l•min^{-1} (60±ml•kg^{-1}•min^{-1}) and 4.63±0.21 l•min^{-1} (59±6 ml•kg^{-1}•min^{-1}) at 3 and 10 days post-transfusion, respectively. No significant relationship was found between the individual change in RCV and Hb with $\dot{V}O_2$ max values to post-transfusion. Heat stress tests (HSTs) were administered approximately 2 wk pre- and 48 h post-infusion. After 30 min of rest in a 20°C antechamber, the HSTs consisted of a 120 min exposure (two repeats of 15 min rest and 45 min treadmill walking) in a hot (35°C, 45% rh) environment while euhydrated. The following observations were made: 1) the increased erythrocyte volume was associated with a reduction in plasma volume (PV) and maintained the same blood volume as during the pre-infusion measurements; 2) polycythemia reduced total circulating protein, but did not alter F-cell ratio, plasma osmolality, plasma protein content, or plasma lactate at rest or during exercise-heat stress; 3) polycythemia did not change the volume of fluid entering the intravascular space from rest to exercise-heat stress; 4) polycythemia tended to reduce the rate of heat storage during exercise-heat stress; 5) polycythemia caused an improved local sweating response. We conclude that induced polycythemia can have an ergogenic effect by increasing maximal aerobic power and enhancing the thermoregulatory response during exercise heat stress.

INTRODUCTION

It is believed that several recent Summer Olympic medal winners have used erythrocyte reinfusions (homologous and autologous) or "blood doping" as an ergogenic aid. These athletes participated in endurance events which required high maximal aerobic power and made considerable thermoregulatory demands for heat dissipation. Therefore, erythrocyte reinfusions may acutely improve exercise performance by oxygen transport as well as thermoregulatory mechanisms.

Buick et al. (3) conclusively demonstrated that acute polycythemia improves an individual's submaximal and maximal exercise performance in a comfortable temperature environment. Subsequent studies have confirmed these findings in comfortable temperature normoxic (19, 26, 27) as well as hypoxic (27) environments. These studies used erythrocyte freeze-preservation (40, 41) for autologous reinfusion (at least 2 units) following the re-establishment of normocythemia. The physiological mechanism believed primarily responsible for the improved aerobic performance is increased arterial oxygen content (17); however, it is possible that blood volume expansion may also contribute to these ergogenic effects (20,36). Blood volume measurements (from independent measurements of plasma and erythrocyte volume) have not been obtained in previous erythrocyte reinfusion studies, but Kanstrup and Ekblom (20) have measured erythrocyte volume (^{51}Cr). Based on erythrocyte volume measurements, these investigators calculated that blood volume had increased after erythrocyte reinfusion (20). Likewise, two recent animal studies (one measured only plasma volume and the other measured both erythrocyte and plasma volume) also support the concept of an expanded blood volume after erythrocyte reinfusion (36,43).

Regardless of the physiological mechanism(s) responsible, surprisingly little detailed information is available which describes the magnitude of increase in maximal

aerobic power elicited by acute polycythemia. Several important questions concerning the ergogenic effects of acute polycythemia have not been addressed. For example, it is not known if the post-reinfusion increase in maximal aerobic power is: 1) evident in all individuals; 2) related to the change in hemoglobin concentration; and 3) modified by the individual's initial level of aerobic fitness. Answers to these questions might be obtained from an examination of existing data; however, integration of these data is difficult because only mean data of the pertinent variables are presented in most reports (3,20,26,27).

The influence of acute polycythemia on thermoregulatory responses during exercise-heat stress has not been studied. However, there are several reasons why erythrocyte reinfusion may be beneficial to individuals performing exercise in the heat. During exercise-heat stress, core temperature increases as a consequence of the metabolic and environmental heat load. To minimize these core temperature changes, vasomotor adjustments occur to increase skin blood flow, and dilate superficial veins. These adjustments not only facilitate sensible and insensible heat loss, but also displace a portion of the central blood volume to the cutaneous vasculature. Under conditions of combined exercise-heat stress, a competition may exist between the circulatory requirements of metabolically active skeletal muscle and the cutaneous vasculature (29,32). Eventually this competition can compromise cardiac output as well as heat dissipation (27,29). Therefore, an intervention which increases arterial oxygen content as well as blood volume might improve exercise-heat performance. Increased arterial oxygen content will improve muscle oxygenation at any level of muscle blood flow, and an expanded blood volume will allow a higher stroke volume and cardiac output. Finally, most investigators believe that during exercise core temperature responses are coupled to relative exercise intensity (9,30). Erythrocyte reinfusion has been shown to increase maximal aerobic power (3,20,26,27,39):

therefore, the relative exercise intensity and thus core temperature would be lower during exercise at a given exercise intensity.

This report summarizes a series of experiments conducted to determine the effects of erythrocyte reinfusion on maximal aerobic power and thermoregulatory responses during exercise-heat stress. In addition, we have attempted, via our own research and by obtaining data from other research laboratories to determine the physiological mechanisms responsible for, and factors that might modify, the ergogenic effects of erythrocyte reinfusion on maximal aerobic power.

MILITARY RELEVANCE

The Special Forces is a military group having many missions that require high aerobic demand. These individuals must frequently engage in sustained high intensity operations, such as forced marches with heavy backpack loads. Additionally, Special Forces must be prepared to meet a variety of unusual mission requirements. With little notice, the Special Forces could be assigned a mission requiring great aerobic demands when their immediate physical training was directed toward another component of fitness (e.g., strength training). Marked improvements in maximal aerobic power would generally require several weeks of intense training (25), which unfortunately may also be associated with manpower attrition due to orthopedic injuries (2). Therefore, any intervention which can immediately increase maximal aerobic power without manpower attrition has great application to the Special Forces. Erythrocyte reinfusion has recently been demonstrated to improve an individual's maximal aerobic power and submaximal endurance capacity (16,17). Therefore, its use as an ergogenic aid may have military application for small groups of Special Forces. Previous studies which have used autologous erythrocyte reinfusion have not employed

subject populations or environmental conditions which enable determination of its military application for the Special Forces.

The U.S. Army and Navy must be prepared to engage in military operations under hot environmental conditions. During these operations soldiers engage in a variety of tasks that require physical exercise. It is well established that exercise performance in hot environments is reduced below levels achieved in neutral thermal environments. As a result, the U.S. Army and Navy is interested in methods to improve exercise performance in the heat. Erythrocyte reinfusion has been successfully used to improve exercise performance under neutral thermal and hypoxic conditions. Based upon knowledge of physiological mechanisms limiting exercise performance in the heat, it is probable that erythrocyte reinfusion would be an ergogenic aid in the heat as well. Physiological mechanisms by which erythrocyte reinfusion could improve exercise performance in the heat include an increased stroke volume, increased cutaneous blood flow, increased oxygen content of the blood, an improved sweating response, and a decreased relative oxygen uptake at the same level of exercise.

An interesting aspect from the military point of view about employing erythrocyte reinfusion as an ergogenic aid is the duration of its action. Previous investigations have reported that blood volume expansion elevated oxygen carrying capacity (3,26,27) and improved aerobic exercise performance (3) for periods of up to 16 weeks. However, it should be emphasized that caution needs to be employed when evaluating these durations of action until additional research has been reported in the scientific literature. If erythrocyte reinfusion improves exercise performance in the heat for time periods approximating 1-4 weeks, its application would be for small groups of the Special Forces or Rapid Deployment Forces employed in hot environmental conditions (e.g., the Middle East). These operations would probably be vigorous in nature and last for relatively short durations.

METHODS

Subjects. Nine fit male volunteers from the 10th Special Forces Group (Ft. Devens, MA) participated in this investigation. These subjects were all members of the same team and therefore were exposed to similar physical activity, environmental extremes and diet throughout the study. The subjects were divided into a reinfusion and a saline group. The reinfusion group (n=6) had a mean (±SD) age of 30 ± 7 yr (including the 43 yr old platoon sergeant), weight of 79 ± 9 kg, surface area-to-mass ratio of 254 ± 14 $cm^2 \cdot kg^{-1}$, and percent body fat of 15 ± 5. The saline group (n=3) had a mean (±SD) age of 22 ± 1 yr, weight of 83 ± 20 kg, surface area-to-mass ratio of 246 ± 26 $cm^2 \cdot kg^{-1}$, and percent body fat of 15 ± 4.

Protocol. During the late fall and early winter months, two units of blood were removed by phlebotomy from each subject. A minimum of six weeks separated the removal of each blood unit. During the subsequent spring months, the experimental portion of the study was completed. Initially, the subjects were familiarized with the test procedures, their percent body fat was determined by hydrostatic weighing, and they completed practice exercise tests. Several days prior to pre-testing, the subjects' erythrocyte volume and plasma volume were measured. The pre-testing included a maximal aerobic power test and a heat stress test, which were completed on separate days. Approximately two weeks (range 10-17 days) later each subject received an infusion. The reinfusion group received ~600 ml of a sodium chloride-glucose-phosphate solution containing ~50% Hct (autologous erythrocytes), whereas the saline group received ~600 ml of the sodium chloride-glucose-phosphate solution only. Erythrocyte volume and plasma volume were measured 24 h post-reinfusion, the heat stress test was administered 48 h post-reinfusion, and a maximal aerobic power test was completed 72 h post-reinfusion. Also, another maximal aerobic power test was completed 10 days post-reinfusion. (Figure 1).

Blood storage, reinfusion, as well as erythrocyte volume and plasma volume measurements were conducted at the Naval Blood Research Laboratory, Boston, MA. After each phlebotomy, the blood was separated into its erythrocyte and plasma components, and the erythrocytes were frozen with 40% w/v glycerol and stored at minus 80°C (40,41). For the reinfusion group, approximately 600 ml of autologous erythrocytes in a sodium chloride-glucose-phosphate solution were administered over a 1-hour period, after the frozen cell component was thawed and washed to reduce the glycerol concentration to less than 1%. The erythrocyte oxygen transport function was determined from the erythrocyte 2,3 DPG, ATP and in vitro P_{50} measurements (42). For the saline group, a similar time period was used to administer the sodium-chloride-glucose-phosphate solution. During the reinfusion, all subjects were blindfolded and wore earphones. Neither the subjects nor the investigators at the U.S. Army Research Institute of Environmental Medicine were aware of the identity or size of the saline and reinfusion groups.

The maximal aerobic power and heat stress tests were conducted at the U.S. Army Research Institute of Environmental Medicine. Each subject's maximal aerobic power was determined by a progressive intensity, continuous effort treadmill test. The warm-up bout consisted of four min of walking (1.56 $m \cdot s^{-1}$) at a 4% treadmill grade. The subjects then ran (3.13 $m \cdot s^{-1}$) continuously at an initial grade of 5% with 2-1/2% increments every two min. Established criteria were employed for determination of maximal oxygen uptake (38). These tests were conducted in a comfortable (20°C ambient temperature, 40% relative humidity) environment.

Heat stress tests (Figure 2) were conducted in a hot (35°C ambient temperature, 45% relative humidity) environment. This environment was selected to enable both insensible as well as some sensible heat exchange. Each HST was 120 min (two repeats of 15 min rest and 45 min exercise) in duration. During exercise,

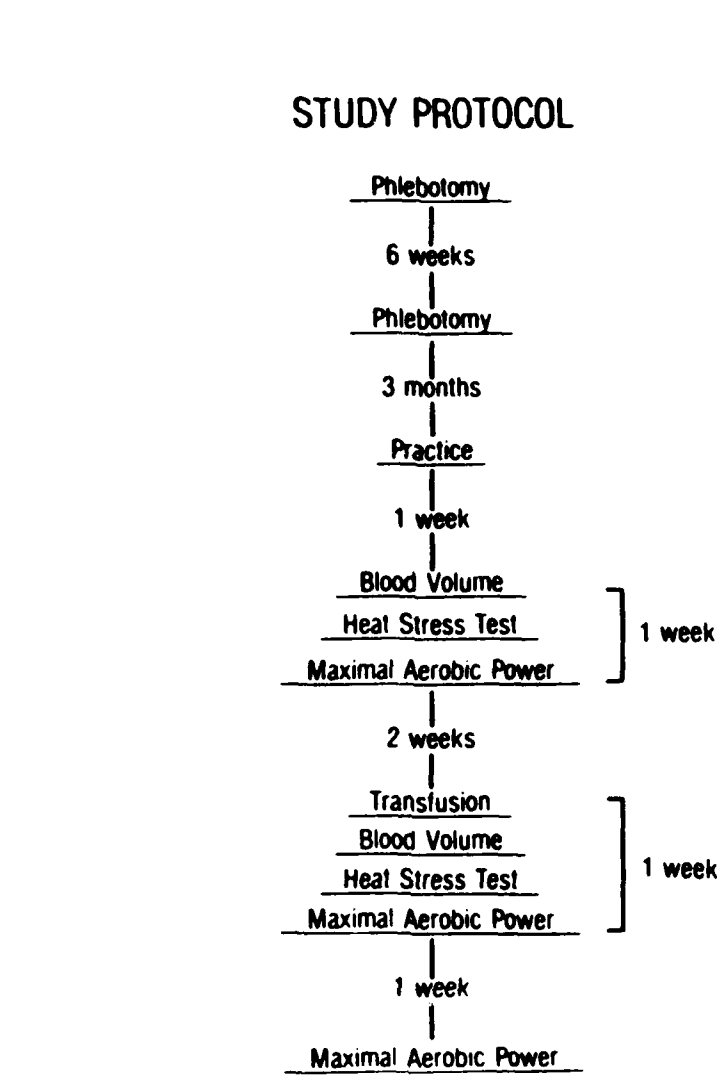

Figure 1. Schematic outline of the study design.

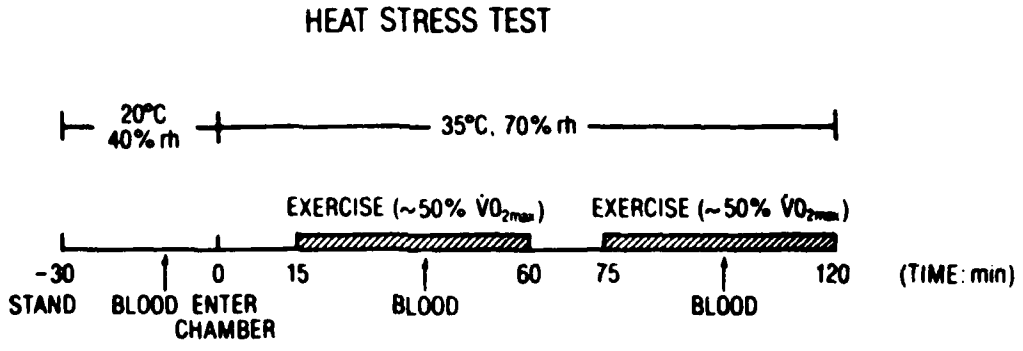

Figure 2. Schematic outline of the Heat Stress Test protocol.

subjects walked (1.56 $m \cdot s^{-1}$) on an inclined (6% grade) treadmill. During the rest periods they were weighed and rehydrated with spring water to maintain their initial body weight (i.e., euhydration). The subjects wore only shorts and tennis shoes. At least 10 days separated the pre- and post-reinfusion HSTs to minimize any partial acclimation from the initial heat exposure.

Measurements. Electrocardiogram was obtained with chest electrodes (CM5 placement) and radiotelemetered to an oscilloscope-cardiotachometer unit (Hewlett-Packard). During the maximal aerobic power tests, an automated system (Sensormedics Horizon MMC) was used to measure oxygen uptake. During the HSTs, the respiratory gases were collected in 150-liter Douglas bags. The volume of expired gases was measured with a Tissot gasometer, and the O_2 and CO_2 concentrations were measured with an electrochemical O_2 analyzer (Applied Electrochemistry 5-3A) and an infrared CO_2 analyzer (Beckman LB-2), respectively. Body fat was determined by hydrostatic weighing.

During the HSTs, core temperature (T_c) measurements were obtained from both the rectum and esophagus (T_{es}). Rectal temperature was measured from a thermistor inserted ~10 cm beyond the anal sphincter and esophageal temperature was measured from a thermistor placed in a catheter at heart level. Unfortunately, two subjects, from the saline group, were unable to swallow the esophageal thermistor. Skin temperatures were obtained with a three-point thermocouple skin harness (chest, calf, and forearm), and mean weighted skin temperature was calculated (35). The dew point temperature of the upper arm was continually measured by an automatic sensor (18). Body weights were determined on a K-120 Sauter precision electronic balance (accuracy $\pm$ 10 g). Total body sweating rates ($\dot{M}$) were calculated from nude body weight loss adjusted for water intake and urine output. The rate of total body heat storage (S) was calculated by the equation:

$$S = \Delta T_b \Delta t^{-1} \cdot 0.97 \cdot mb \cdot A_D^{-1}$$

where: ΔT_b (20) is the change in mean body temperature ($\Delta T_b = 0.9\Delta T_c + 0.1\Delta T_{sk}$). Δt is change in time. 0.97 is specific heat content of the body ($W \bullet h \bullet kg^{-1} \bullet {}^{o}C^{-1}$). mb is body mass (kg) and A_D is body surface area (m^2). Arm sensible (radiative and convective, R+C) heat exchange was determined by using the sum of arm heat transfer coefficients (h_{cj}, $W \bullet m^{-2} \bullet {}^{o}C^{-1}$), and a linear radiation heat transfer coefficient (h_{rj}, taken as 4.4 to 4.7 $W \bullet m^{-2} \bullet {}^{o}C^{-1}$) multiplied by the gradient between arm skin temperature and the ambient temperature. An average local area convective heat transfer of 7.3 $W \bullet m^{-2} \bullet {}^{o}C^{-1}$ as determined by naphthalene sublimation (23) was used.

Venous blood samples were collected from an indwelling Teflon catheter placed within a superficial forearm vein. Patency was maintained with heparinized saline; the catheter (2 ml of dead space) was flushed with 4 ml of blood before each 5 ml sample was obtained. Blood samples taken at rest were obtained while the subjects stood (for 20 min prior to sampling) in the antechamber (20°C ambient temperature, 40% relative humidity), and exercise blood samples were obtained 30 min into each exercise bout while the subjects continued to walk. Triplicate measurements were made for all blood variables. Automated systems were used to measure hemoglobin (Hemoglobinometer, Coulter Electronics) and plasma lactate (Model 23 Lactate Analyzer, YSI). Plasma osmolality was measured by freezing point depression (Osmette A, Precision Systems) and plasma protein concentration was quantitated with a refractometer (American Optical). The percent change in plasma volume from rest to exercise was calculated from the appropriate hemoglobin and hematocrit values (11). erythrocyte volume (RCV) and plasma volume (PV) at rest were measured by the radioactively labelled chromium (^{51}Cr) and iodine labelled albumin (^{125}I) methods (42), respectively. The plasma volumes during exercise were calculated by adjusting the measured plasma volume at rest by the appropriate relative percent change in plasma volume. The F-cell ratio (5) was calculated from the ratio of overall

hematocrit (H_O) to the peripheral venous hematocrit (not corrected for trapped plasma). The overall hematocrit was calculated as:

$$H_O = \frac{RCV}{RCV + PV}$$

Statistical Analyses. Means, standard deviations, simple regression, multiple regression and repeated measures analyses of variance followed by Bonferroni (t) procedures were used. Statistical significance was accepted at the $p<0.05$ level. It was not our intent to make direct comparisons between the saline and reinfusion groups; therefore, an unbalanced experimental design was selected. The saline group was used to control for the influence of partial heat acclimation during the study as well as to provide an index of pre- to post-reinfusion measurement variability.

RESULTS

Reinfusion. Table 1 provides the subjects' *resting* hematological measurements for pre- and post-reinfusion. For the reinfusion group, there were increases ($p<0.05$) in erythrocyte volume by 11%, hemoglobin by 10%, and hematocrit by 12% from pre- to post- erythrocyte reinfusion. Figure 3 indicates that the increased erythrocyte volume (222 ml) was associated ($r=-0.72$) with a reduced plasma volume (265 ml) from pre- to post-reinfusion. Neither blood volume nor F-cell ratio was altered by reinfusion. For the reinfusion group, no difference was found for erythrocyte 2,3 DPG, from pre- to post-reinfusion (Table 2). Since the actual transfused erythrocyte volume was 299 $\pm$ 17 ml, the percent survival rate was 74 $\pm$ 19%. However, calculation of the survival rate from the transfused erythrocyte volume is known to result in large experimental error. For the saline group, there was decreased ($p<0.05$) erythrocyte volume by 3% and blood volume by 4% from pre- to post-reinfusion.

Table 1. Influence of erythrocyte or saline reinfusion on hematological variables at rest.

		Red Cell Volume (ℓ)	Plasma Volume (ℓ)	Blood Volume (ℓ)	Hemoglobin ($g \cdot dl^{-1}$)	Venous Hematocrit (%)	F-Cell ($H_O \cdot H_v^{-1}$)
REINFUSION(n=6)							
Pre-	$\bar{x}$	2.079	3.674	5.753	13.9	42	0.89
	SD	0.258	0.285	0.425	1.1	3	0.06
Post-	$\bar{x}$	2.301	3.409	5.710	15.3	47	0.87
	SD	0.234	0.238	0.451	1.1	2	0.03
SALINE(n=3)							
Pre-	$\bar{x}$	2.158	3.463	5.621	14.9	44	0.88
	SD	0.358	0.661	1.015	0.6	2	0.01
Post-	$\bar{x}$	2.093	3.311	5.403	14.9	44	0.89
	SD	0.335	0.625	0.954	0.8	2	0.02

H_O is overall hematocrit and H_v is venous hematocrit.

Table 2. Influence of erythrocyte or saline reinfusion on red blood cell function.

	2, 3 DPG (μmol • g Hb^{-1})	ATP (μmol • g Hb^{-1})	P_{50} (mmHg)
REINFUSION (n=6)			
Pre-			
$\bar{x}$	15.3	4.2	27
SD	2.3	0.5	2
Post-			
$\bar{x}$	14.4	4.2	27
SD	2.0	0.8	1
SALINE (n=3)			
Pre-			
$\bar{x}$	13.6	3.5	27
SD	2.3	0.4	1
Post-			
$\bar{x}$	14.4	3.5	27
SD	1.6	0.4	1

Maximal Aerobic Power. Table 3 provides the subjects' physiological response to maximal effort treadmill exercise before and after saline or erythrocyte reinfusion. For the saline group, heart rate, ventilatory equivalent of oxygen and maximal oxygen uptake were not altered by reinfusion. For the reinfusion group, maximal oxygen uptake was increased ($p<0.05$) by ~11% at approximately 3 days (Post-A) and by ~8% at 10 days (Post-B) post-reinfusion. Figure 4 presents the reinfusion subjects' individual changes in maximal oxygen uptake to the Post-A and Post-B tests. It should be noted that one subject did not improve his maximal aerobic power post-reinfusion. That individual was a 43-year old. Figure 5 depicts the individual relationship between the increase in erythrocyte volume and increase in maximal aerobic power for the Post-A test. An insignificant ($p>0.05$, $r = -0.47$) relationship was found between these variables.

Data were compiled from four investigations to examine the influence of erythrocyte reinfusion on maximal aerobic power (3,26,27,39). These investigations all employed similar procedures in which: 1) the reinfused autologous erythrocytes were the product of two blood units; 2) the erythrocytes were freeze preserved (40); 3) the reinfusion did not precede re-establishment of normocythemia; and 4) the maximal oxygen uptake was measured within 24 to 72 h after reinfusion. This time period enabled sufficient equilibration of body fluids between compartments after the reinfusion, and is well within the period of peak ergogenic effects (17).

Table 4 presents a description of the 30 subjects who participated in the four investigations and whose data have been used in the analyses. The male subjects from Study I (3) were national and international caliber track athletes who were very fit. Studies II (39) and III (present study) used moderately fit male populations. We were unable to find published data on the influence of erythrocyte reinfusion on relatively unfit male populations. Data were available, however, on the effects of

Table 3. Effect of erythrocyte or saline reinfusion on Special Forces physiological responses to maximal exercise.

	Heart Rate ($b \cdot min^{-1}$)			Ventilatory Equivalent ($\dot{V}E \cdot \dot{V}O_2^{-1}$)			Maximal Oxygen Uptake ($\ell \cdot min^{-1}$)			($ml \cdot kg^{-1} \cdot min^{-1}$)		
	Pre	Post-A	Post B	Pre	Post-A	Post-B	Pre	Post-A	Post-B	Pre	Post-A	Post-B
RED CELL (n=6)												
$\bar{x}$	190	185	181	37	34	35	4.280	4.753*	4.631*	54	60*	59*
SD	7	9	12	2	3	4	0.215	0.426	0.217	5	6	6
SALINE (n=3)												
$\bar{x}$	197	193	189	35	35	37	4.670	4.714	4.831	56	57	58
SD	2	5	6	5	4	3	1.073	0.837	1.145	4	4	4

Post-A and Post-B refer to tests of 3 days and 10 days post infusion.
*$P<0.05$

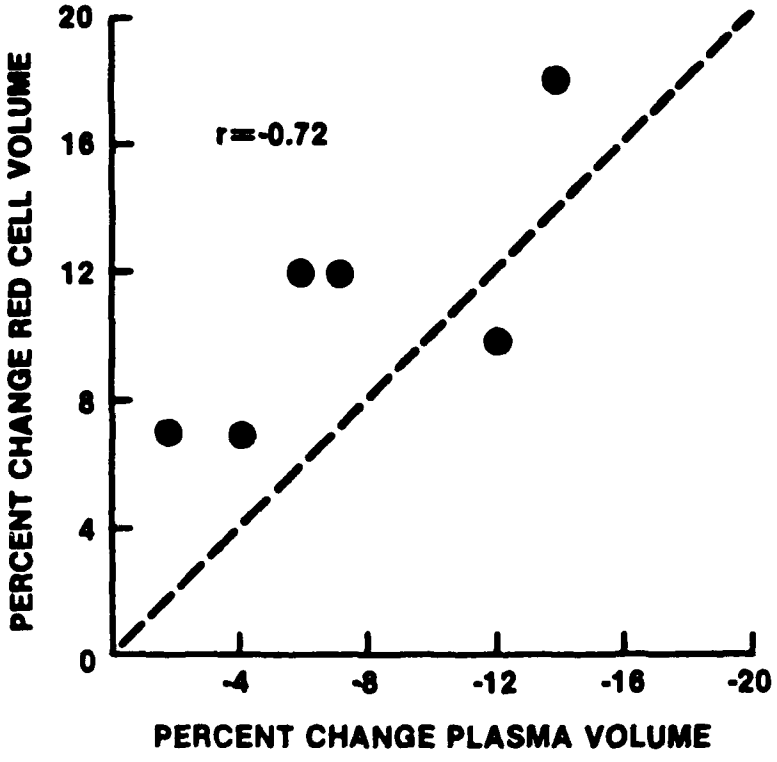

Figure 3. The relationship between the percent change in erythrocyte volume and the percent change in plasma volume after erythrocyte reinfusion.

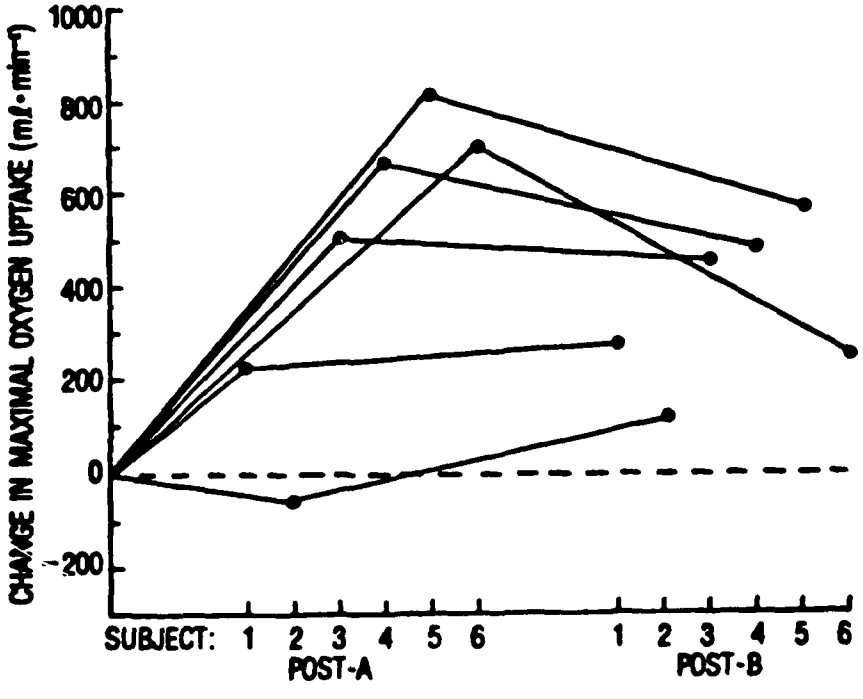

Figure 4. Individual changes in maximal oxygen uptake from the pre-reinfusion (base line) to the post-reinfusion A (3 days) and B (10 days) tests.

Table 4. Description of the subject population and test methods.

Study	n	Gender	Age (yr)	Height (cm)	Weight (kg)	Percent Body Fat (%)	Exercise Mode	Initial Maximal Aerobic Power ($ml \cdot kg^{-1} \cdot min^{-1}$)
1. Buick et al. (3)								
$\bar{x}$	11	M	21	175	64	7	TM	80
SD			3	4	5	1		6
II. Thomson et. al. (39)								
$\bar{x}$	4	M	23	177	71	-	TM	56
SD			1	7	6	-		7
III. Sawka et al. (31)								
$\bar{x}$	6	M	30	182	79	15	TM	54
SD			7	4	9	5		5
IV. Robertson et al. (26)								
$\bar{x}$	9	F	23	167	56	-	CY	43
SD			2	7	3	-		4

TM is treadmill exercise and CY is cycle exercise.

erythrocyte reinfusion for a female population with low fitness (26). Despite the existence of gender differences for maximal aerobic power and hemoglobin concentration, we decided to include this female population (Study IV) in our data presentation. This enabled us to examine the individual responses of a large population encompassing very fit to low fit individuals.

For each study that employed control experiments, maximal oxygen uptake was not altered by saline infusion (3,26,27). Figure 6 presents the individual data for maximal aerobic power (ml $O_2 \cdot kg \cdot^{-1} min^{-1}$) measured before and shortly after (24 to 72 h) erythrocyte reinfusion. Maximal aerobic power was increased ($p<0.01$) from 60.6 $\pm$ 16.3 to 65.4 $\pm$ 16.1 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$, and Studies II and III had greater ($p<0.05$) increases than Studies I and IV from pre- to post-reinfusion. A correlation coefficient of $r=0.99$ ($p<0.01$) was found between the pre- and post-reinfusion values. An increased maximal aerobic power was observed in 29 of 30 subjects; only a 43-year old individual failed to show an increment. To our knowledge, this person is the oldest to have received an erythrocyte reinfusion and subsequently to have his maximal oxygen uptake measured. The 43-year old individual's data have not been included in the statistical analyses of Figures 4 and 5, but are plotted for reference.

Figure 7 presents the relationship between an individual's initial aerobic power and the percent increase for that value subsequent to erythrocyte reinfusion. An analysis of variance indicated a difference ($p<0.01$) among the groups for the percent increase in maximal aerobic power. Study I had a smaller ($p<0.05$) percent increase than Studies II, III and IV. This smaller improvement for "very fit" individuals, however, may reflect a bias from a larger denominator in the percent increase calculation. To adjust for this possible bias, Figure 8 presents the relationship between an individual's initial aerobic power and the absolute ($\ell \cdot min^{-1}$) increase in maximal oxygen uptake subsequent to erythrocyte reinfusion. An analysis of variance

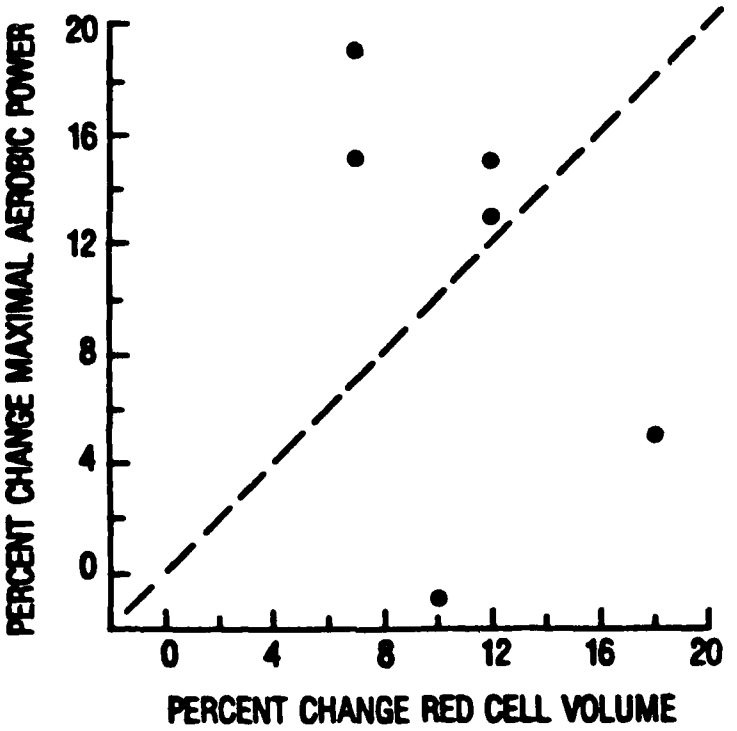

Figure 5. Individual data for the relationship between the increase in erythrocyte volume and increase in maximal aerobic power for the Post-A test. The broken line represents the line of equality.

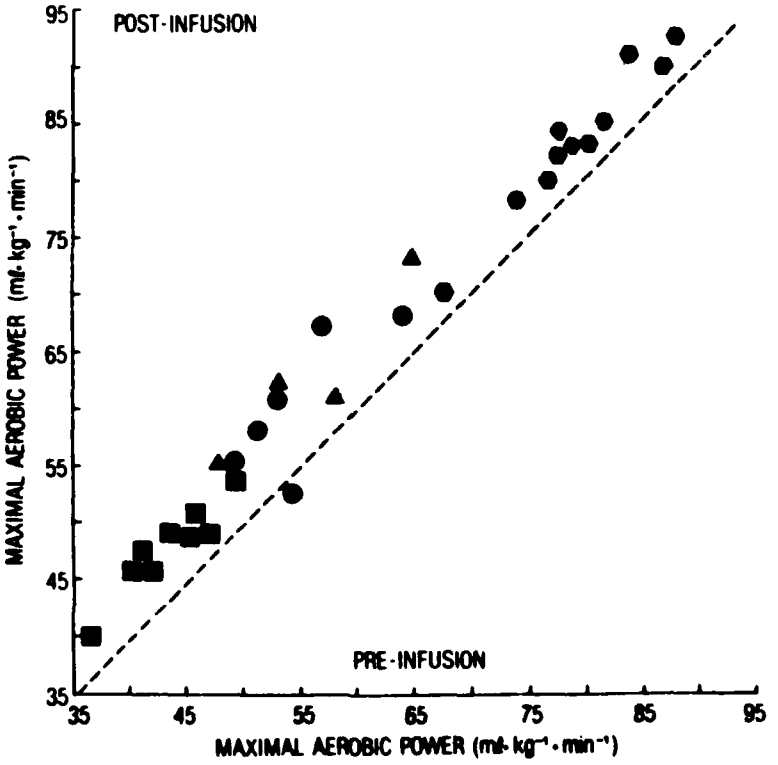

Figure 6. Individual data for maximal aerobic power measured before and after erythrocyte reinfusion. The broken line represents the line of equality. Hexagons indicate Study I (3), triangles, Study II (39), circles, Study III (present study), and squares, Study IV (26).

indicated a difference ($p<0.01$) among the studies for the absolute increment in maximal oxygen uptake. Study I had a smaller ($p<0.05$) increase than Study III, and Study IV had a smaller ($p<0.05$) increase than Studies II and III. These data suggest that moderately fit (Studies II and III) individuals have an accentuated increase in maximal oxygen uptake after erythrocyte reinfusion.

Hemoglobin data were available for Studies I, II and III. Erythrocyte reinfusion resulted in an increased ($p<0.01$) hemoglobin concentration (1.36 ± 0.55g Hb•100 ml of blood^{-1}) which corresponds to a 10 ± 5 percent increase. No differences were found among the three studies for the increase in hemoglobin concentration after reinfusion. Figure 9 presents individual data for the percent change in hemoglobin and the percent change in maximal aerobic power values. Figure 10 presents the individual data for the absolute change in hemoglobin and the absolute change in maximal aerobic power ($\dot{V}O_2$•min^{-1}) values. It can be noted that the 43-year old individual, who was the only individual whose maximal aerobic power did not increase, had an increase in hemoglobin concentration of only 0.7 g Hb•100 ml of blood^{-1}. Table 5 presents the correlation coefficients between the subjects' change in hemoglobin and change in maximal oxygen uptake ($\dot{V}O_2$•min^{-1}) after erythrocyte reinfusion. No significant relationships were found between these variables.

Heat Stress Tests. In the present study, all nine subjects completed (120 min) each HST. Table 5 provides the subjects' physiological responses to the HSTs. For the reinfusion group, metabolic rate and mean skin temperature were not altered, but final exercise heart rate was reduced ($p<0.05$) from pre- to post-reinfusion. No differences were found for final exercise rectal temperature (38.7 ± 0.6 to $38.5 \pm 0.2^{\circ}$C) nor final exercise esophageal temperature (38.3 ± 0.5 to $38.0 \pm 0.1^{\circ}$C) from pre- to post-reinfusion. The heat storage as calculated from rectal temperature changes was lower ($p<0.05$) for the first, but not the second exercise bout during the

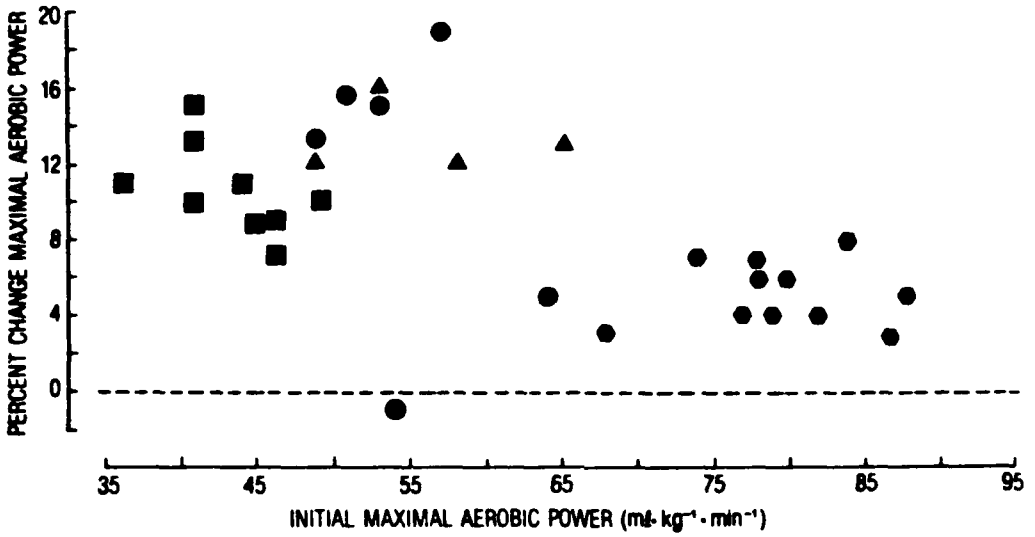

Figure 7. Individual data for the relationship between initial (pre-reinfusion) maximal aerobic power and the percent increase in maximal aerobic power after erythrocyte reinfusion. Hexagons indicate Study I (3), triangles, Study II (39), circles, Study III (present study), and squares, Study IV (26). The broken line represents no change in maximal aerobic power.

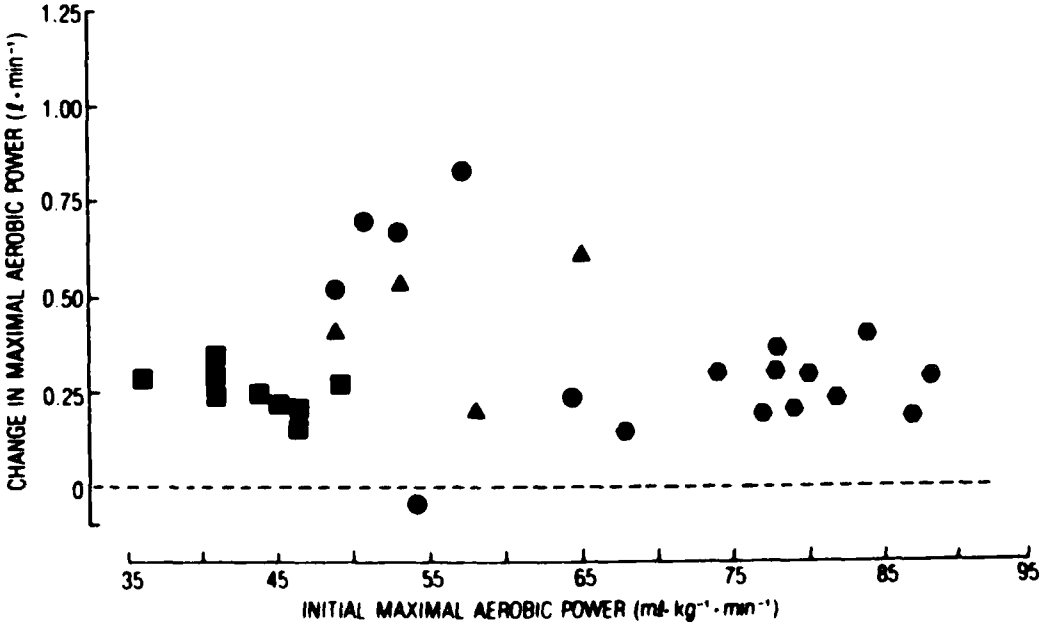

Figure 8. Individual data for the relationship between initial (pre-reinfusion) maximal aerobic power and the absolute ($\ell\ O_2 \cdot min^{-1}$) increase in maximal aerobic power after erythrocyte reinfusion. Hexagons indicate Study I (3), triangles, Study II (39), circles, Study III (present study), and squares, Study IV (26). The broken line represents no change in maximal aerobic power.

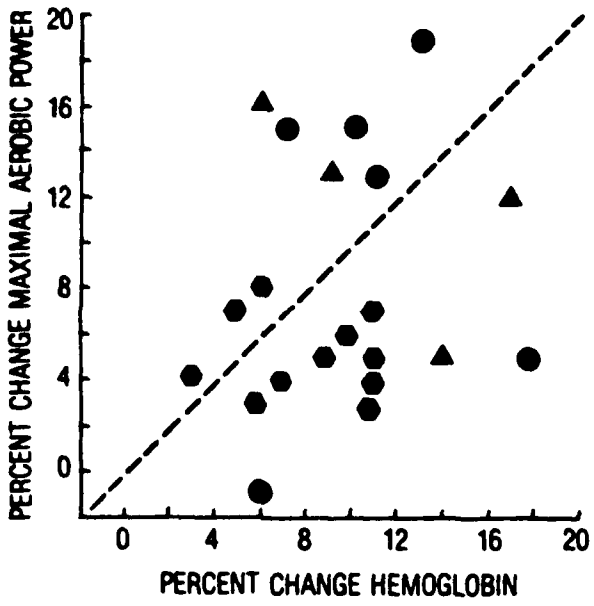

Figure 9. Individual data for the relationship between percent change in hemoglobin concentration and percent change in maximal aerobic power after erythrocyte reinfusion. Hexagons indicate Study I (3), triangles, Study II (39), circles, Study III (present study), and squares, Study IV (26). The broken line represents the line of equality.

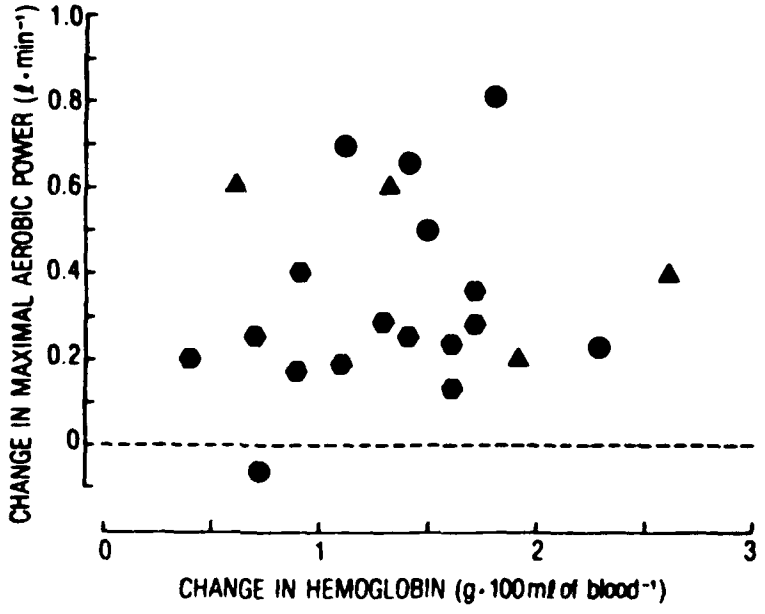

Figure 10. Individual data for the relationship between the absolute change in hemoglobin concentration and absolute change in maximal aerobic power after erythrocyte reinfusion. Hexagons indicate Study I (3), triangles, Study II (39), circles, Study III (present study), and squares, Study IV (26). The broken line represents no change in maximal aerobic power.

Table 5. Correlation coefficients (r) between the subjects' change in hemoglobin (Hb) and change in maximal oxygen uptake ($\dot{V}O_2$ max) after erythrocyte reinfusion.

	% Δ Hb vs. % Δ $\dot{V}O_2$ max	Δ Hb vs. Δ $\dot{V}O_2$ max	Δ Hb vs. % Δ $\dot{V}O_2$ max	% Δ Hb vs. Δ $\dot{V}O_2$ max
STUDY I (3) (n=11)	0.06	0.07	- 0.05	0.07
STUDY II(39) (n=4)	-0.63	-0.65	-0.53	-0.74
STUDY III(26)	0.50	0.48	0.25	0.54
Total (n=21)	0.27	0.11	0.14	0.35

Δ Hb is change in hemoglobin ($g \cdot 100\ ml^{-1}$): % Δ Hb is percent change in hemoglobin: Δ $\dot{V}O_2$ is change in maximal oxygen uptake ($\ell \cdot min^{-1}$): % Δ $\dot{V}O_2$ is percent change in maximal oxygen uptake.

post-reinfusion HST. The rate of heat storage as calculated from esophageal temperature changes tended to be lower ($p>0.05$) post-reinfusion and is depicted in Figure 11. Eleven of the twelve observations (six subjects x two exercise bouts) demonstrated lower values post-reinfusion.

Table 7 provides the subjects steady-state heat exchange during the HSTs. For the reinfusion group, total body sweating rate, insensible heat loss (arm E_{sk}) and sensible heat loss were not significantly altered from pre- to post erythrocyte reinfusion. However, Table 7 shows that the onset time for sweating ($\dot{m}_s$) was earlier ($p<0.05$) post reinfusion. Also, the total skin conductance (H_{sk}) was greater ($p<0.05$) during the transient phase of exercise I and exercise II in the HST post reinfusion, as shown in figure 12. Figure 13 is the plot of the arm sweating ($\dot{m}_s$) response to esophageal temperature (T_{es}).

Figure 14 presents the reinfusion group's plasma volume and percent change in plasma volume from rest to exercise during the HSTs. The percent change in plasma volume from rest to exercise was greater ($p<0.01$) post-reinfusion, but the absolute fluid volume that moved from the interstitial to the intravascular space was nearly identical (~190 ml) pre- and post-reinfusion. Table 8 presents the plasma osmolality, plasma lactate, plasma protein content and total circulating protein during the HSTs. For the reinfusion group, plasma osmolality, plasma lactate and plasma protein content were not altered from pre- to post-reinfusion. However, total circulating protein was lower ($p<0.01$) post-reinfusion.

For the saline group, none of the variables listed in Tables 6 through 8, nor plasma volume and percent change in plasma volume from rest to exercise were altered by reinfusion.

Table 6. Influence of erythrocyte or saline reinfusion on physiological measurements during the Heat Stress (35°C. 45% rh) Exercise Tests.

	Metabolic Rate ($W \cdot m^{-2}$)	Heart Rate ($b \cdot min^{-1}$)		Skin Temperature (°C)		ΔS_{re} ($W \cdot m^{-2}$)		ΔS_{es} ($W \cdot m^{-2}$)	
		Ex-1	Ex-2	Ex-1	Ex-2	Ex-1	Ex-2	Ex-1	Ex-2
REINFUSION (n=6)									
Pre-									
$\bar{x}$	358	139	145	33.5	33.3	72	29	65	72
SD	25	15	19	0.4	0.5	11	11	11	39
Post-									
$\bar{x}$	349	132	141	33.9	34.0	63	29	55	43
SD	28	15	13	0.9	0.8	9	5	15	5
SALINE (n=3)									
Pre-									
$\bar{x}$	352	144	151	33.2	33.2	58	58	-	-
SD	50	6	7	0.6	0.7	1	27	-	-
Post-									
$\bar{x}$	352	145	158	33.6	34.0	63	67	-	-
SD	41	2	9	0.4	0.7	19	41	-	-

ΔS is heat storage, calculated using rectal temperature (T_{re}). and esophageal temperature (T_{es}).
Ex-1 and Ex-2 are exercise bouts 1 and 2, respectively.

Table 7. Influence of erythrocyte or saline reinfusion on heat exchange measurements during the Heat Stress (35°C, 45% rh) Exercise Tests.

	Arm (R + C) ($W \cdot m^{-2}$)		Arm E_{sk} ($W \cdot m^{-2}$)		Sweating Rate Onset Time (min)		Total Body Sweating Rate ($g \cdot m^{-2} \cdot h^{-1}$)	
	Ex-1	Ex-2	Ex-1	Ex-2	Ex-1	Ex-2	Ex-1	Ex-2
REINFUSION (n=6)								
Pre								
$\bar{x}$	-12.0	-0.6	240	375	4.8	2.4	386	581
SD	12.0	8.0	34	29	0.9	1.0	52	46
Post								
$\bar{x}$	-14.9	-10.0	240	359	1.5	1.4	384	559
SD	6.2	5.9	38	32	0.8	0.7	58	49
SALINE (n=3)								
Pre-								
$\bar{x}$	23.9	-18.4	263	335	-	-	420	524
SD	8.2	7.5	46	25	-	-	72	36
Post								
$\bar{x}$	-17.8	-12.6	258	330	-	-	411	559
SD	3.0	8.8	11	79	-	-	20	59

Ex-1 and Ex-2 are exercise bouts 1 and 2, respectively. Arm sensible (radiative and convective, R+C) and insensible (evaporative from skin, E_{sk})heat exchange values represent steady-state (final exercise) values.

Table 8. Influence of erythrocyte or saline reinfusion on plasma osmolality, plasma lactate, plasma protein and total circulating protein during the Heat Stress (35°C, 45% rh) Exercise Tests.

		Osmolality (mosmol • kg^{-1})			Lactate (mmol • ℓ$^{-1}$)			Protein Content (g • dl^{-1})			Total Circulating Protein (g)		
		Rest	Ex-1	Ex-2	Rest	Ex-1	Ex-2	Rest	Ex-1	Ex-2	Rest	Ex-1	Ex-2
REINFUSION (n=6)													
Pre-													
	$\bar{x}$	285	288	289	1.1	1.3	1.1	8.1	7.8	8.0	299	298	308
	SD	2	2	3	0.3	0.3	0.5	0.7	0.5	0.5	34	37	29
Post-													
	$\bar{x}$	287	288	289	1.2	1.5	1.4	8.3	7.8	8.0	284	283	287
	SD	3	3	4	0.3	0.6	0.4	0.6	0.5	0.5	36	36	36
SALINE (n=3)													
Pre-													
	$\bar{x}$	286	287	289	1.7	1.2	1.3	7.9	7.7	7.9	274	267	275
	SD	0	6	4	0.2	0.1	0.1	0.3	0.2	0.1	48	58	58
Post-													
	$\bar{x}$	286	291	288	1.2	1.4	1.3	8.2	7.7	7.9	272	269	272
	SD	2	3	5	0.3	0.1	0.2	0.3	0.2	0.1	58	53	56

Ex-1 and Ex-2 are exercise bouts 1 and 2, respectively.

Table 9. Anthropometric description of the Special Forces subjects.

	Age (yr)	Height (cm)	Weight (kg)	Surface Area (m^2)	%Fat SF	%Fat UW	LBM (kg)
$\bar{x}$	27.3	180.5	79.4	2.00	15.7	15.1	67.2
SD	5.7	7.1	11.4	0.17	4.6	4.0	8.0
RANGE:							
min	22.0	168.0	60.7	1.68	8.0	7.0	53.4
max (n=12)	43.0	190.0	95.8	2.24	23.0	21.0	79.2

SF is the % fat calculated from the skinfold measurements and; UW is %fat determined from underwater weighing measurements; LBM is lean body mass.

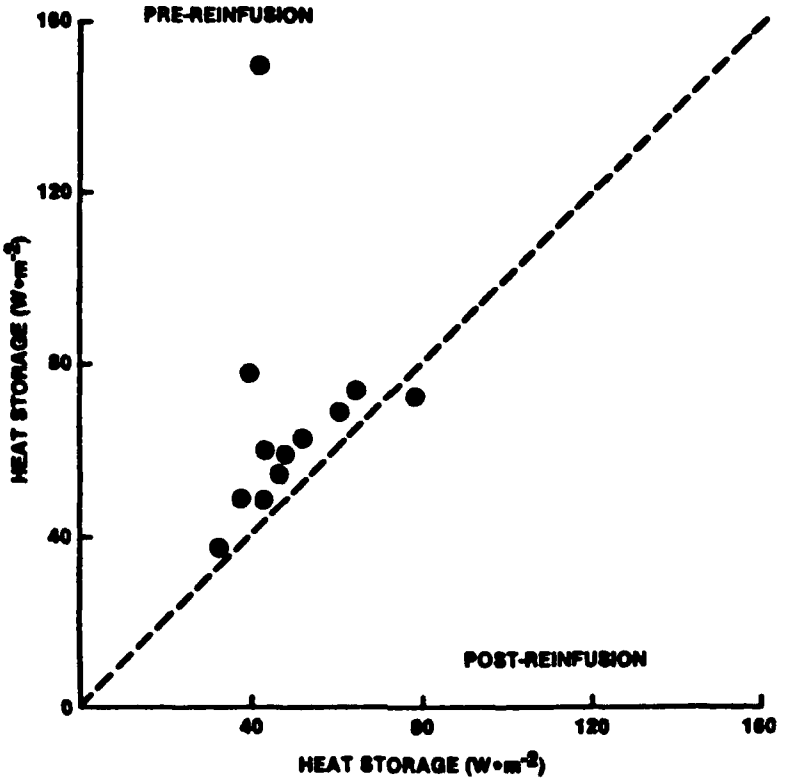

Figure 11. Individual data plots of pre- to post-reinfusion values for heat storage (calculated from esophageal temperature) during the Heat Stress Tests.

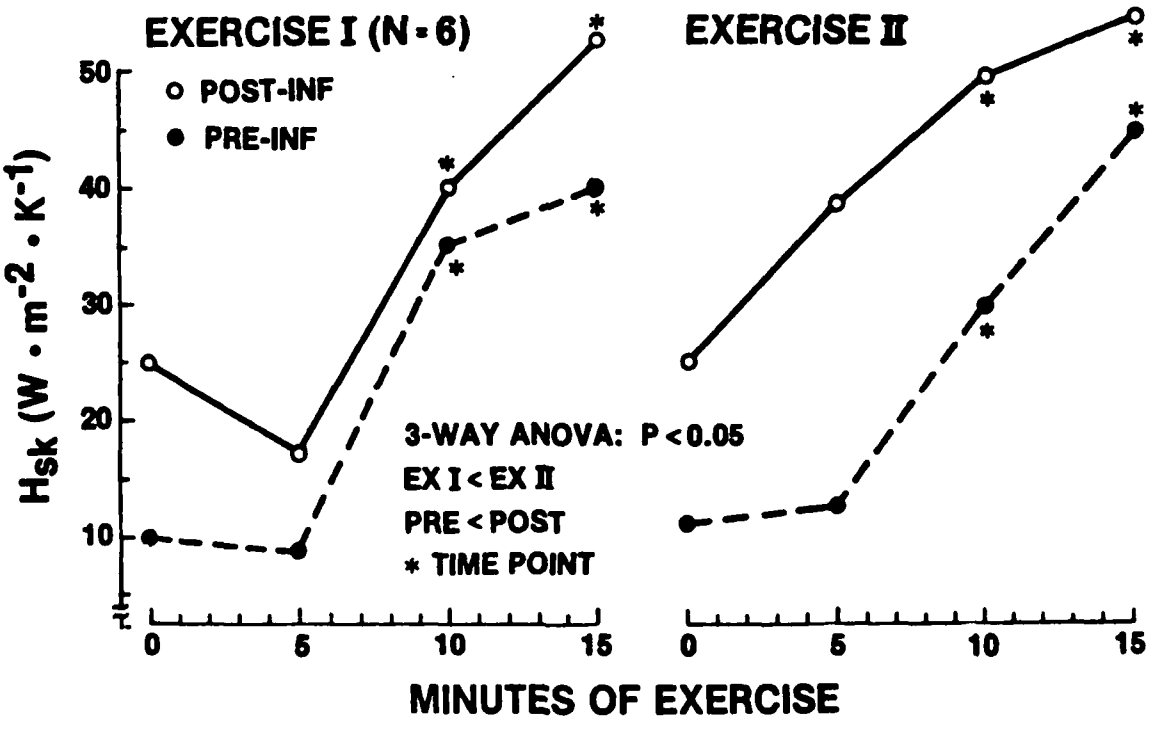

Figure 12. The mean total skin conductance during the first 15 minutes of each exercise of the HSTs pre- and post- erythrocyte reinfusion.

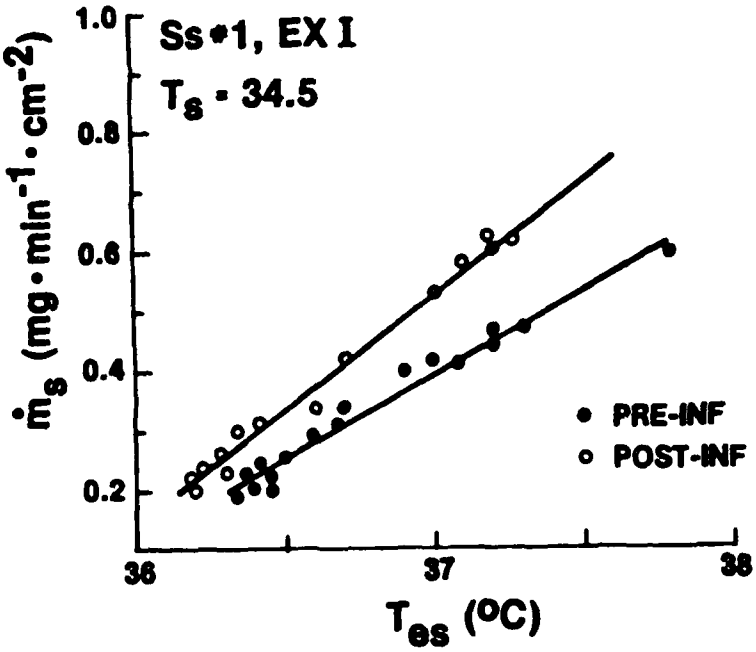

Figure 13. A typical arm sweating response of one subject to esophageal temperature during the first exercise bout prior to and post erythrocyte reinfusion.

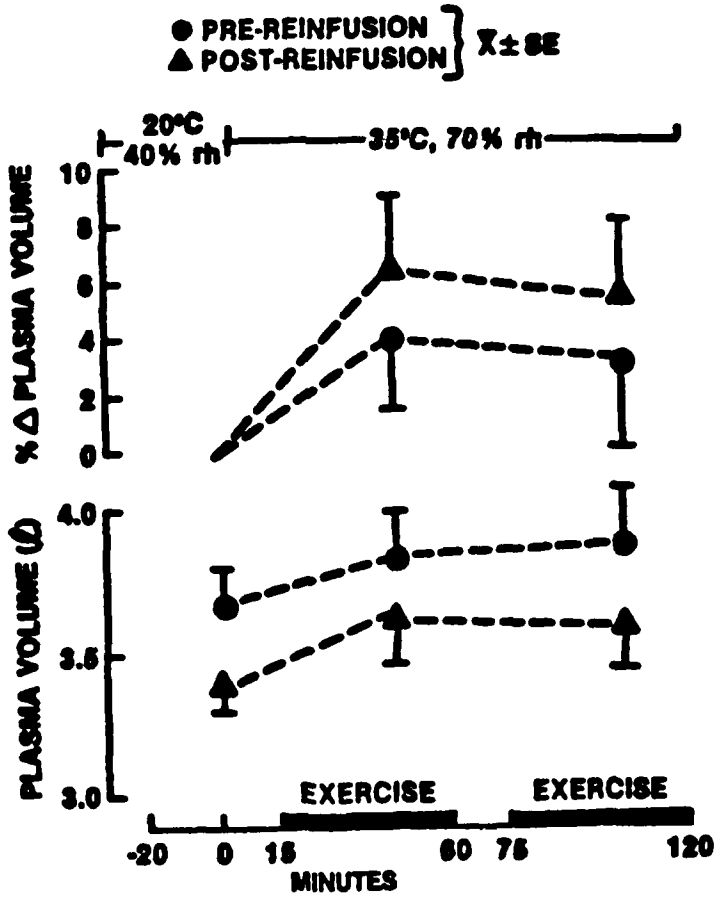

Figure 14. Plasma volume and the percent change in plasma volume from rest during the pre- and post-reinfusion Heat Stress Tests.

DISCUSSION

Special Forces. This report presents maximal aerobic power (Table 3) and anthropometric (Table 9) values on a selective segment of the U.S. Army population, a Special Forces Team. Generally, these Special Forces soldiers were older, taller and of greater body weight and lean body mass than typical soldiers in a combat infantry division (44). These apparent anthropometric differences may be related to occupational training and job skill requirements. Members of a Special Forces team are all volunteers and selection to a team is contingent upon the soldier's successful completion of a physically intense occupational training program.

The Special Forces soldiers also tended to have higher levels of aerobic fitness (pre-reinfusion) than those previously reported for combat infantry soldiers (44). The Special Forces team we studied had spent nearly fifty percent of its training schedule conducting physically intensive field exercise during the five months preceding the study. In garrison, the Special Forces soldiers participated in an organized physical training program which included approximately 30 km of running, 3 h of calesthenics and weight circuit training and 1 h team sports each week. These Special Forces soldiers had a mean maximal aerobic power of 55 $ml \cdot kg \cdot^{-1} \cdot min^{-1}$, which corresponds to a "high aerobic fitness" (25) for their age and sex. Consequently, the Special Forces' occupational and physical training programs appear to provide an effective physical challenge for development and maintenance of high levels of aerobic fitness. However, soldiers who volunteer for Special Forces duty may have high levels of aerobic fitness before entering the Special Forces training program and thus their training may not improve their aerobic fitness.

To our knowledge, this Special Forces team is the most aerobically fit U.S. Military unit reported to date (44,45). This observation supports an earlier finding

that the physical intensity of military occupations plays a role in the eventual level of aerobic fitness (44). Military units with special missions may, by the nature of their duties, attain and maintain a high level of aerobic fitness in some members or attract individuals already having high fitness levels. Support for this is found in a study of British paratroopers between the age of 21-48 yr who had a mean maximal oxygen uptake of 58.5 $ml \cdot kg^{-1} \cdot min^{-1}$ (45).

Aerobic Power. The factors which may modify the increase in maximal oxygen uptake induced by erythrocyte reinfusion have not been fully elucidated. This report has presented individual data from 30 subjects (3, 26, 27, 39) who represent a range from low to very high aerobic fitness. Nearly identical methods were used for blood storage and reinfusion, but some differences existed among the protocols used to elicit maximal oxygen uptake. Therefore, some inter-study differences might exist for the maximal oxygen uptake increments. These four studies, however, were all conducted by experienced investigators in established laboratories, and we have confidence in the comparability of these values. It should be noted that the low-fit group were females and that collaborative data should be obtained from a group of low-fit males during treadmill exercise. However, the data have been coded for each study so they can be included or excluded by the reader when interpreting the results.

Erythrocyte reinfusion increased maximal oxygen uptake for 29 of the 30 subjects. The magnitude of the increase in maximal oxygen uptake was related to the subject's initial fitness level. Individuals with an initial aerobic power between ~50 to ~65 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ appear to have the greatest response to erythrocyte reinfusion (Figure 8). For the nine subjects in Studies II and III who responded to erythrocyte reinfusion, maximal oxygen uptake increased by 0.515 $\pm$0.204 $\ell \cdot min^{-1}$ which represents about ~94% of the theoretical maximal potential for increase. These moderate to high fit individuals were probably sufficiently trained to have a greater

potential to increase both oxygen delivery and extraction to optimally increase their maximal oxygen uptake after erythrocyte reinfusion (19,39).

Individuals with an initial aerobic power below 50 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ and above 65 ml $O_2 \cdot kg^{-1}$ displayed a very homogeneous but blunted increase in maximal oxygen uptake after erythrocyte reinfusion (Figure 9). Both the low-fit (Study IV) and extremely-fit (Study I) individuals demonstrated approximately 50% of the increased maximal oxygen uptake shown by the moderately-fit individuals. Subjects in Studies I and IV had increases in maximal oxygen uptake of 0.249 ± 0.046 and 0.261 ± 0.080 $\ell \cdot min^{-1}$, respectively. The physiological mechanism(s) responsible for the blunted increase in maximal oxygen uptake after erythrocyte reinfusion are probably different for each group. The low-fit individuals may not have the central reserves (ability to deliver oxygen) or peripheral reserves (ability to extract and utilize oxygen at the skeletal muscle) to fully use the increased arterial oxygen content (available after erythrocyte reinfusion) during *maximal effort* exercise. The most likely explanation, however, is a lack of peripheral (insufficient oxidative capacity) rather than central responsiveness in the low-fit group. In contrast, the very-fit individuals might already be effectively using (without erythrocyte reinfusion) a comparatively larger portion of their potential central and peripheral reserves during maximal exercise.

The blunted increase in maximal oxygen uptake by highly fit subjects (i.e., $\dot{V}O_2$ max greater than 65 $ml \cdot kg^{-1} \cdot min^{-1}$) may be due to an exercise-induced arterial hypoxemia. Dempsey et al. (10) reported that in highly trained endurance runners there was a tendency for their arterial blood to desaturate at maximal exercise, and therefore limit their aerobic performance. The arterial hypoxemia they noted with the increasing alveolar to arterial (A-a) PO_2 difference (22-35 mmHg) during high intensity exercise may be attributed to a diffusion limitation. A diffusion limitation may occur either when the erythrocyte transit time in the pulmonary capillary decreases or the

blood-gas barrier thickens, so that the O_2 diffusing across the blood-gas barrier does not have time to equilibrate with the capillary blood. Dempsey (10) suggests that during maximal exercise the highly fit subjects may experience a decrease in the erythrocyte transit time in the pulmonary capillary to the point that diffusion limitation occurs. Other explanations for the increasing A-a PO_2 difference include a venous admixture and $\dot{V}A/\dot{Q}$ inequality; however, their contribution to the A-a difference during exercise at sea level are minimal (46,47).

Erythrocyte reinfusion increased hemoglobin concentration by approximately 1.36 g•100 ml of blood^{-1}, which corresponds to an increased arterial oxygen content of ~1.82 ml O_2•100 ml of blood^{-1} (1.36 g Hb x 1.34 ml O_2•g Hb^{-1}). It is likely that our subject sample may have achieved an average cardiac output approximating 30 ℓ•min^{-1} during maximal exercise (27). A maximal exercise eliciting a theoretical cardiac output of 30 ℓ•min^{-1} would result in an additional 0.546 ℓ O_2•min^{-1} available to the tissues after erythrocyte reinfusion. Also, if erythrocyte reinfusion increased maximal cardiac output (17, 39) then this theoretical volume of oxygen available to the tissues would be accentuated. However, an increased maximal oxygen uptake is also dependent upon the peripheral tissue's ability to extract and utilize the additional oxygen which is made available (19). Overall, erythrocyte reinfusion increased maximal oxygen uptake by an average of 0.357 $\pm$ 0.216 ℓ•min^{-1}, which represents ~65% of the theoretical maximal potential for increase at a cardiac output of 30 ℓ•min^{-1}.

Surprisingly, there were no significant relationships between the increase in hemoglobin concentration and the increase in maximal oxygen uptake (Table 5). The lack of significant relationships may, in part, be due to the homogeneity in the volume of infused erythrocytes; each subject received the product of two blood units. However, this is unlikely since the range of increase for hemoglobin concentration after

erythrocyte reinfusion was fairly wide (from 0.6 to 2.6 g Hb•100 ml of blood ^{1}). Alternatively, individual differences may exist for the amount of additional oxygen which is made available to the contracting skeletal musculature during maximal exercise. For example, erythrocyte reinfusion may cause varied effects on maximal cardiac output as well as vasomotor responses (at a given cardiac output) directing blood to the contracting musculature. Two studies (13,26) however, have reported that erythrocyte reinfusion does not affect the cardiac output during maximal exercise. The mechanism by which erythrocyte reinfusion might increase maximal cardiac output would be by an expanded blood volume causing an increased myocardial pre-load. However, we found that erythrocyte reinfusion does not alter blood volume during either rest or exercise (27). Furthermore, some of the subjects may not have sufficient peripheral tissue adaptations, such as available capillary to skeletal muscle fiber exchange surface area or enzymatic oxidative potential, to use the additional oxygen which is available (19,39). It is known that aerobic training is associated with increased capillarization, increased number and size of mitochondria as well as increased concentration and activity of oxidative enzymes in skeletal muscle (19,39).

Plasma Volume. Our study indicates that erythrocyte reinfusion results in a compensatory reduction in plasma volume (Figure 3). The reinfused subjects had an increased erythrocyte volume and decreased plasma volume of 222 ml and 265 ml, respectively. Interestingly, the saline group manifested a decreased erythrocyte volume and plasma volume from pre- to post-reinfusion. This observation raises the possibility that systematically decreased post-reinfusion measurements may have masked a slight increase in blood volume for the reinfusion group. Bentley and Lewis (1) independently measured erythrocyte volume (^{51}Cr) and plasma volume (^{125}I) in 130 patients with polycythemia and a variety of other hematological disorders. They found a positive linear relationship ($p<0.01$) between venous hematocrit and total

blood volume in patients with venous hematocrits of greater than 50%, but in patients with lower hematocrits no relationship was found between these variables. Bentley and Lewis (1) also observed that for individuals with venous hematocrits of ~40% or less there is an inverse ($r=-0.75$; $p<0.01$) relationship between venous hematocrit and plasma volume. Our subjects had initial venous hematocrits of 42% (range 37 to 45%); therefore, the compensatory reduction in plasma volume for the increased erythrocyte volume ($r=-0.72$) was consistent with the clinical data from Bentley and Lewis (1). It seems possible that the plasma volume responses to erythrocyte reinfusion may somehow be dependent on the initial pre-reinfusion hematocrit.

Valeri and Altschule (42) have reported that an erythrocyte transfusion can increase plasma volume in trauma patients. As erythrocytes do not exert an in vitro oncotic pressure, they reported that the expanded plasma volume from erythrocyte transfusion was mediated by a mobilization of interstitial albumin into the intravascular space (41,42,43). It can be noted that their protein-mediated plasma volume expansion in trauma patients is nearly identical to that mechanism contributing to heat acclimation hypervolemia (37). Interestingly, the patients were wounded servicemen who had been transported from southeast Asia usually within the preceding two weeks. These individuals were probably heat acclimated from living in a warm climate. Our subjects were unacclimated to heat; in fact, they had participated in cold weather training before and during the study. Perhaps, if heat acclimated subjects were reinfused, their greater availability of extravascular protein (37) might have allowed a plasma volume expansion.

During the post-reinfusion HSTs, the reinfused subjects had a reduced (~7%) plasma volume with the same blood volume as in the pre-reinfusion HST. This reduced plasma volume did not affect the absolute magnitude (~190 ml) of

hemodilution resulting from the transition of rest to exercise. Therefore, plasma volume per se does not exert an effect independent of blood volume on vascular fluid shifts during exercise-heat stress. This observation is of interest, but not surprising since the transcapillary osmotic, oncotic and probably hydrostatic pressures were not different from pre- to post-reinfusion. On the other hand, several investigators (14,20) have shown that manipulation of plasma volume to change blood volume will alter vascular fluid shifts during exercise. Finally, the approximate 7% reduction in plasma volume is similar in magnitude to the reduction associated with the hypovolemia during moderate hypohydration (35). As a result, it might be interesting to examine the hematological responses of reinfused subjects who had the additional challenge of hypohydration during exercise-heat stress.

Thermoregulation. Our study is important in that we examined the influence of acute polycythemia on thermoregulation during exercise-heat stress. Our data indicate that polycythemia provides a small thermoregulatory advantage for euhydrated non-heat-acclimated individuals. Heat storage values, as calculated from esophageal temperatures, were lower post-reinfusion for 11 of 12 observations. Heat storage values as calculated from rectal temperature were only lower during the first exercise bout for the reinfusion group. For the saline group, a tendency for a greater rate of heat storage was evident during the post-reinfusion HST.

The relative contributions of insensible and sensible heat exchange for the reduced rate of heat storage after erythrocyte reinfusion are unclear. Neither total body sweating rate, steady-state arm E_{sk}, nor steady-state arm (R+C) values differed between the two conditions. These steady-state measurements may not have been sufficiently sensitive to detect small differences; alternatively, both insensible and sensible heat loss from the arm may not always follow changes in other body regions (14,33). Finally, the improved effector responses for heat loss may have occurred at

the onset of exercise (lower threshold responses) and therefore would not be evident from the steady-state measurements. During steady-state conditions, by definition, heat loss should be roughly equal to heat gain.

The sweating rate ($\dot{m}_s$) onset time was earlier during exercise for post reinfusion HSTs. This reduced sweat gland latency may be due to a better priming or initial filling of the sweat gland duct (4). This response may reflect the changes seen in the total circulating proteins after erythrocyte reinfusion. After reinfusion, the total circulating proteins decreased rapidly, which may reflect a translocation of protein from the intravascular to the interstitial space. This increased interstitial protein would facilitate better hydration of these tissues. If proteins were partially translocated into the cutaneous interstitial space, the interstitial fluid would increase and provide more precursor fluid for sweat secretion and subsequently improve the sweating onset time.

The higher total skin conductance (H_{sk}) post erythrocyte reinfusion indicates a greater efficiency in total heat transferred from the skin. The H_{sk} was calculated using both sensible and insensible components ($H_{sk}=[arm(R+C) + \dot{m}_s \times 408]/(T_{es}-T_{sk})$). Since the arm (R + C) showed no significant differences, it is likely that the major factor responsible for the improved heat transfer post reinfusion was the insensible heat loss.

We hypothesize a potential physiological mechanism for improved sensible heat exchange after erythrocyte reinfusion; namely that the elevated arterial oxygen content allowed a reduced skeletal muscle blood flow, and thus increased cutaneous blood flow at a given cardiac output during submaximal exercise. Welch et al. (48) found that a 10% increase in arterial oxygen content during hyperoxia in humans resulted in a similar decrease in muscle blood flow during submaximal exercise. Likewise, several studies using dogs have reported similar findings of reduced skeletal muscle blood flow

when arterial oxygen content was elevated by hyperoxia during submaximal exercise (46,49).

CONCLUSION

In conclusion following erythrocyte reinfusion the following observations are made on unacclimated subjects: 1) the increase in hemoglobin concentration is fairly homogeneous; 2) nearly all individuals demonstrate an increase in maximal oxygen uptake; 3) the magnitude of increase in hemoglobin concentration is not related to the magnitude of increase in maximal oxygen uptake; and 4) the magnitude of increase in maximal oxygen uptake is related to the individual's initial aerobic fitness; 5) the increased erythrocyte volume was associated with a reduction in plasma volume to maintain the same blood volume as during the pre-reinfusion measurements; 6) polycythemia reduced total circulating protein, but did not alter F-cell ratio, plasma osmolality, plasma protein content, or plasma lactate at rest or during exercise-heat stress; 7) polycythemia did not change the volume of fluid entering the intravascular space from rest to exercise-heat stress; 8) polycythemia tended to reduce the rate of heat storage during exercise-heat stress; and 9) after erythrocyte reinfusion the local sweating rate onset time was earlier during exercise in the heat. These results should not be generalized beyond euhydrated subjects who are unacclimated to heat.

REFERENCES

1. Bentley, S.A. and S.M. Lewis. The relationship between total red cell volume, plasma volume and venous hematocrit. Brit. J. Haematol. 33:301-307, 1976.
2. Brudrig, T.J., T.D. Gudger and L. Obermeyer. Stress fractures in 295 trainees: A one-year study of incidence as related to age, sex and race. Mil. Med. 148:666-667, 1983.
3. Buick, F.J., N. Gledhill, A.B. Froese, L. Spiret and E.C. Meyers. Effect of induced erythrocythemia on aerobic work capacity. J. Appl. Physiol. 48:636-642, 1980.
4. Bullard, R.W. Studies on human sweat gland duct filling and skin hydration. J. Physiologie (Paris) 63:218-221, 1971.
5. Chaplin, H., P.L. Mollison and H. Vetter. The body/venous hematocrit ratio: its consistency over a wide hematocrit range. J. Clin. Invest. 32:1309-1316, 1953.
6. Clausen, J.P. Circulatory adjustments to dynamic exercise and effects of physical training in normal subjects and in patients with coronary artery disease. Prog. Card. Dis. 18:459-495, 1976.
7. Cote, R.W., J.B. Bomar, G.E. Robertshaw and T.C. Thomas. Maximal aerobic power in women cadets at the U.S. Air Force Academy. Aviat. Space Environ. Med. 48:154-155, 1977.
8. Daniels, W.L., D.M. Kowal, J.A. Vogel and R.M. Stauffer. Physiological effects of a military training program on male and female cadets. Aviat. Space Environ. Med. 50:562-566, 1979.
9. Davies, C.T.M., J.R. Brotherhood and E. Zeidifard. Temperature regulation during severe exercise with some observations on effects of skin wetting. J. Appl. Physiol. 41:772-776, 1976.

10. Dempsey, J.A., P.G. Hanson and K.S. Henderson. Exercise-induced arterial hypoxaemia in healthy human subjects at sea level. J. Appl. Physiol. 355: 161-175, 1984.

11. Dill, D.B. and D.L. Costill. Calculation of percentage changes in volumes of blood, plasma and red cells in dehydration. J. Appl. Physiol. 37:247-248, 1974.

12. Durnin, J.V.G.A., and J. Womersley. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. Br. J. Nutr. 37:247-248, 1974.

13. Ekblom, B., G. Wilson, P-O Åstrand. Central circulation during exercise after venesection and reinfusion of red blood cells. J. Appl. Physiol. 40:379-383, 1976.

14. Fortney, S.M., E.R. Nadel, C.B. Wenger and J.R. Bove. Effect of blood volume on sweating rate and body fluids in exercising humans. J. Appl. Physiol. 51:1594-1600, 1981.

15. Glantz, S.A. *Primer of Biostatistics*. New York,NY: McGraw-Hill, 1981, pp.87-90.

16. Gledhill, N. Blood doping and related issues: a brief review. Med. Sci. Sports Exerc. 14:183-189, 1982.

17. Gledhill, N. The influence of altered blood volume and oxygen transport capacity on aerobic performance. In: Exerc. Sport Sci. Rev., New York: MacMillan 13:75-93, 1985.

18. Graichen, H., R. Rascati and R.R. Gonzalez. Automatic dew-point temperature sensor. J. Appl. Physiol. 52:1658-1660, 1982.

19. Holloszy, J.O. Biochemical adaptations to exercise aerobic metabolism. In:Exerc. Sport Sci. Rev. New York: Academic Press, 1:45-71, 1973.

20. Kanstrup, I. and B. Ekblom. Blood volume and hemoglobin concentration as determinants of maximal aerobic power. Med. Sci. Sports Exerc. 16:256-262, 1984.

21. Minard, D. Body heat content. In: Physiological and Behavioral Temperature Regulation, edited by J.D. Hardy, A.P. Gagge and J.A.J. Stolwijk. Springfield, IL: Thomas 1970, p. 345-357.

22. Mohsenin, V. and R.R. Gonzalez. Tissue pressure and plasma oncotic pressure limit the fluid shift in exercise. J. Appl. Physiol. 56:102-108, 1984.

23. Nishi, Y. and A.P. Gagge. Direct evaluation of convective heat transfer coefficient by naphthalene sublimation. J. Appl. Physiol. 29:830-838, 1970.

24. Patton, J.F., W.L. Daniels, and J.A. Vogel. Aerobic power and body fat of men and women during army basic training. Aviat. Space Environ. Med. 51:492-496, 1980.

25. Pollock, M.S. The quantification of endurance training programs. Exerc. Sport Sci. Rev. 1:155-188, 1973.

26. Robertson, R.J., R. Gilcher, K.F. Metz, C.J. Caspersen, T.G. Allison, R.A. Abbott, G.S. Skrinar, J.R. Kraus and P.A. Nixon. Hemoglobin concentration and aerobic work capacity in women following induced erythrocythemia. J. Appl. Physiol. 57:568-575, 1984.

27. Robertson, R.J., R. Gilcher, K.F. Metz, G.S. Skrinar, T.G. Allison, H.T. Bahnson, R.A. Abbott, R. Becker and J.E. Falkel. Effect of induced erythrocythemia on hypoxia tolerance during physical exercise. J. Appl. Physiol. 53:490-495, 1982.

28. Rowell, L.B.: Circulation. Med. Sci. Sports Exerc. 1:15-22, 1969.

29. Rowell, L.B. Human cardiovascular adjustments to exercise and thermal stress. Physiol. Rev. 54:75-159, 1974.

30. Saltin, B. and L. Hermansen. Esophageal, rectal and muscle temperature during exercise. J. Appl. Physiol. 21:1757-1762, 1966.

31. Sawka, M.N., R.C. Dennis, R.R. Gonzalez, A.J. Young, S.R. Muza, J.W. Martin, C.B. Wenger, R.F. Francesconi, K.B. Pandolf and C.R. Valeri. Influence of

polycythemia on blood volume and thermoregulation during exercise-heat stress. J. Appl. Physiol. 62:1165-1169, 1987.

32. Sawka, M.N. R.P. Francesconi, A.J. Young and K.B. Pandolf. Influence of hydration level and body fluids on exercise performance in the heat. J. Am. Med. Assoc. 252:1165-1169, 1984.

33. Sawka, M.N., R.R. Gonzalez, L.L. Drolet and K.B. Pandolf. Heat exchange during upper and lower body exercise. J. Appl. Physiol. 57:1050-1054, 1984.

34. Sawka, M.N., H. Weber and R.G. Knowlton. The effects of total body submersion on residual lung volume and body density measurements in man. Ergonomics 21:889-894, 1978.

35. Sawka, M.N., A.J. Young, R.P. Francesconi, S.R. Muza and K.B. Pandolf. Thermoregulatory and blood responses during exercise at graded hypohydration levels. J. Appl. Physiol. 59:1394-1401, 1985.

36. Schumacker, P.T., B. Guth, A.J. Suggett, P.D. Wagner and J.B. West. Effects of transfusion-induced polycythemia on O_2 transport during exercise in the dog. J. Appl. Physiol. 58:749-758, 1985.

37. Senay, L.C. Jr. Changes in plasma volume and protein content during exposures of working men to various temperatures before and after acclimation to heat: Separation of the roles of cutaneous and skeletal muscle circulation. J. Physiol. (Lond.) 224:61-81, 1972.

38. Taylor, H.L., E.R. Buskirk and A. Henschel. Maximal oxygen intake as an objective measure of cardiorespiratory performance. J. Appl. Physiol. 8:73-80, 1955.

39. Thomson, J.M., J.A. Stone, A.D. Ginsburg, and P. Hamilton. O_2 transport during exercise following blood reinfusion. J. Appl. Physiol. 53:1213-1219, 1982.

40. Valeri, C.R. Blood Banking and the Use of Frozen Blood Products. Boca Raton, FL: CRC Press, 1976.

41. Valeri, C.R. New developments in red blood cell preservation using liquid and freezing procedures. J. Clin. Lab. Auto. 2:425-439, 1982.

42. Valeri, C.R. and M.D. Altschule. Hypovolemic Anemia of Trauma: The Missing Blood Syndrome. Boca Raton,FL: CRC Press, 1981.

43. Valeri, C.R., K. Donahue, H.M. Feingold, G.P. Cassidy and M.D. Altschule. Increase in plasma volume after the transfusion of washed erythrocytes. Surg. Gynecol. Obstet. 162:30-36, 1986.

44. Vogel, J.A., J.F. Patton, R.P. Mello and W.L. Daniels. An analysis of aerobic capacity in a large United States population. J. Appl. Physiol. 60:494-500, 1986.

45. Vogel, J.A. A review of physical fitness as it pertains to the military service. Technical Report No. 14/85, U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760-5007, 1985.

46. Wagner, P.D. The lungs during exercise. News Physiol. Sci. 2:6-10, 1987.

47. Wagner, P.D., G.E. Gale, R.E. Moon, J.R. Torre-Bueno, B.W. Stolp and H.A. Saltzman. Pulmonary gas exchange in humans exercising at sea level and simulated altitude. J. Appl. Physiol. 61(1): 260-270, 1986.

48. Welch, H.G., J.P. Mullin, G.D. Wilson and J. Lewis. Effects of breathing O_2-enriched gas mixtures on metabolic rate during exercise. Med. Sci. Sports Exerc. 6:26-32, 1974.

49. Welch, H.G., F.B. Petersen, T. Graham, K. Klausen and N. Secher. Effects of hyperoxia on leg blood flow and metabolism during exercise. J. Appl. Physiol. 42:385-390, 1977.

50. Williams, M.H., S. Wesseldine, T. Somma, and R.Schuster. The effect of induced erythrocythemia upon 5-mile treadmill run time. Med. Sci. Sports Exerc. 13:169-175, 1981.

51. Wilson, B.A. and W.N. Stainsby. Effect of O_2 breathing on RQ, blood flow and developed tension in in situ dog muscle. Med. Sci. Sports Exerc. 10:167-170, 1978.

DISTRIBUTION LIST

2 Copies to:

Commander
U.S. Army Medical Research and Development Command
SGRD-RMS
Fort Detrick
Frederick, MD 21701-5012

12 Copies to:

Defense Technical Information Center
ATTN: DTIC-DDA
Alexandria, VA 22304-6145

1 Copy to:

Commandant
Academy of Health Sciences, U.S. Army
ATTN: AHS-COM
Fort Sam Houston, TX 78234

1 Copy to:

Dir of Biol & Med Sciences Division
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

1 Copy to:

CO, Naval Medical R&D Command
National Naval Medical Center
Bethesda, MD 20014

1 Copy to:

HQ AFMSC/SGPA
Brooks AFB, TX 78235

1 Copy to:

Director of Defense Research and Engineering
ATTN: Assistant Director (Environment and Life Sciences)
Washington, DC 20301

1 Copy to:

Dean
School of Medicine Uniformed Services
University of Health Sciences
4301 Jones Bridge Road
Bethesda, MD 20014

DISTRIBUTION LIST

2 Copies to:

Commander
U.S. Army Medical Research Institute of Chemical Defense
Aberdeen Proving Ground, MD 21010-5425

2 Copies to:

Commander
U.S. Army Chemical R&D Center
Aberdeen PRoving Ground, MD 21010-5423

2 Copies to:

Commandant
U.S. Army Chemical School
Ft. McClellan, AL 36205-5000

2 Copies to:

Commander
U.S. Army Medical Research and Development Command
ATTN: SGRD-PLE
Ft. Detrick
Frederick, MD 20701-5012

2 Copies to:

Commander
USAF School of Aerospace Medicine
Brooks Air Force Base, TX 78235

2 Copies to:

Commander
Naval Health Research Center
P.O. Box 85122
San Diego, CA 92138-9174

2 Copies to:

Commander
U.S. Army Biomedical Research and Development Laboratory
Ft. Detrick
Frederick, MD 21701-5010

2 Copies to:

Commander
U.S. Army Medical Materiel Development Laboratory
Ft. Detrick
Frederick, MD 21701-5009

2 Copies to:

Commander
U.S. Army Natick Research, Development and Engineering Center
Natick, MA 01760-5000

2 Copies to:

Commander
10th Special Forces (ABN)
1st Special Forces Group Headquarters
Fort Devens, MA 01433